A Research Proposal

on

Electron acceleration by laser in vacuum and plasmas

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INTRODUCTION

The development in particle accelerators during the past few decades is playing a major role in exploring the properties of subatomic particles. A particle accelerator is a device that accelerates charged particles to very high speeds using electric and /or magnetic fields. The single electron passes through a potential difference of 1.5V, thus gaining 1.5eV of energy considered to be act like accelerator. An ordinary CRT television set is a simple form of accelerator.

In 1931, E.O. Lawrence made the first modern particle accelerator -the cyclotron. This cyclotron was only 4 inches in diameter, and contained two D-shaped magnets separated by a small gap. An oscillating voltage created an electric field across the small gap, which accelerated the particles as they went around the accelerator. The first successful attempt to accelerate the electrons using magnetic induction was made in 1942 by Donald-kerst. His initial betatron reached energies of 2.3 MeV, while subsequent betatron achieved 300 MeV. In 1947, synchrotron radiation was discovered with 70 MeV electron-synchrotrons at General Electric. This radiation was caused by the acceleration of electrons, moving near the speed of light, through a magnetic field. DC accelerator types capable of accelerating particles to speeds sufficient to cause nuclear reactions are Cockcroft-Walton generators or voltage multipliers, which convert AC to high voltage DC, or Van de Graaff generators that use static electricity carried by belts.

Modern accelerators are categories as- Linear and Circular. In linear accelerators, particles are accelerated in a straight line, often with a target at one to create a collision. Circular accelerators propel particles along a circular path using electromagnets until the particles reach desired speeds/energies. Particles are accelerated in one direction around the accelerator, while anti-particles are accelerated in the opposite direction. With beam energy of 1.5 GeV, the first high-energy particle collider was ADONE, which began to operate in 1968. This device accelerates electrons and positrons in opposite directions, effectively doubling the energy of their collision when compared to striking a static target with an electron.

The Large Electron-Positron Collider (LEP) at CERN, which was operational from 1989 to 2000, achieved collision energies of 209 GeV. LEP was a circular electron-positron collider,

built at Cern, Geneva. The ring design (c=27km) meant that the accelerating structures are seen many times by the circulating beams of particles. The ring had 4 experimental sites - ALEPH, DELPHI, L3 and OPAL. The large hadron collider (LHC) uses the same tunnel as LEP, at Cern in Geneva. The machine is a 14TeV proton-proton collider, so each stored beam will have an energy of 7 TeV.

In linear accelerator (LINAC), a microwave is passed through a cylindrical waveguide loaded with periodic rings to slow down the phase velocity of the wave slightly below the velocity of light in vacuum. LINAC yield electron energies up to several tens of MeV. The dimensions of the device are, however huge and the acceleration process is quite slow. This is also true for storage rings and other accelerators. Machines like LHC and ILC are pushing the limits of technology and cost. Making magnets with > 10 Tesla fields is not presently possible.

Acceleration of charged particle by waves has been fascinating field of study for several decades. A wave accelerates co-propagating particles when 1) it exerts a longitudinal force on them 2) its phase velocity is close to velocity of accelerating particles so that the wave field appears quasi-static to the particle and efficient energy transfer to them from the wave could take place.

The intense short pulse laser opens up the possibility to miniaturize the acceleration region and to accelerate electrons at much faster rate.

ELECTRON ACCELERATION IN VACUUM AND PLASMA:

Conventional methods of particle acceleration required huge size to accelerate a particle in vacuum to extremely high energies. Development of efficient method of acceleration would cut both size and cost. In recent years it has been a renewed interest in the possibility of accelerating electrons by laser field in vacuum. This is partly due to the development of ultrahigh power ($\geq$ 10TW), short pulse tabletop laser based on chirped pulse amplification. The development of ultra-high power, short pulse laser based on chirped pulse amplification technique has been intensively pursued for many years. Consequently, there have emerged many new frontier research areas, among them the laser particle acceleration in vacuum and plasma are

very important. A large portion of laser-driven electron acceleration research has focused on plasma based schemes such as the plasma beat wave accelerator and the laser wake field accelerator. As plasma-based schemes can achieve ultrahigh acceleration ($\geq$ 10 GV/m) and offer the possibility of guiding the laser pulse. Laser acceleration in vacuum can eliminate the difficulties associated with the plasma. The possible laser acceleration of relativistic electrons has been extensively analyzed theoretically in the past and recently some schemes have been proposed for experimental verifications.

The intense short pulse laser opens up the possibility to miniaturize, the acceleration region and to accelerate electrons at much faster rate. The idea of using the plasma wave excited by intense laser to accelerate electrons was first suggested by Tajima and Dawson (1979) more than 30 years ago. In the so-called standard laser wake field acceleration schemes, the wake plasma wave is most efficiently generated by the ponderomotive force of the laser pulse when its duration τ_L is close to half of plasma wave period. This is same as acceleration of electrons in vacuum by electromagnetic laser field. There are two routes to it

A) Via the excitation of a plasma wave

B) Direct laser acceleration

In the excitation of plasma wave, a large phase velocity plasma wave is excited by the laser. Laser beat wave accelerator (LBWA) and Laser wake field accelerator (LWFA) follow this route.

In LBWA two collinear lasers with nearby frequencies ω_1 and ω_2 are propagated through an under dense plasma with plasma frequency $\omega_p \approx \omega_1 - \omega_2$. The laser exerts a longitudinal ponderomotive force on the plasma electrons that resonantly drives plasma wave having phase velocity equal to group velocity of the lasers. In LWFA a single laser pulse of short duration, $\tau \approx 2\pi\omega_p^{-1}$, is employed that drives a plasma wave in the wake of the pulse, where $\omega_p = 4\pi ne^2/m$ is the plasma frequency and n, e, m are the density, charge and mass of electron respectively. The electrostatic potential of the plasma wave is comparable to the ponderomotive potential. The modulated laser exerts a ponderomotive force on the electrons enhancing the amplitude of the plasma wave.

The route of the direct laser acceleration exploits the presence of strong self generated magnetic field in the plasma. The electrons make betatron oscillations in the azimuthal magnetic field produced by stream of accelerating electrons. When frequency of betatron oscillations equal to the Doppler shifted laser frequency, as seen by relativistic electrons, a resonance occurs, leading to an effective energy exchange between laser and the electrons. The process requires power significantly higher than critical power for the process of self focusing. The generation of multi-MeV electrons observed by direct laser acceleration in high density plasma channels. Laser acceleration of electrons in vacuum can be realized using the nonlinear or ponderomotive forces associated with the laser electron interaction.

The Lawson-Woodward theorem assumes that the electron is travelling with velocity of light and velocity is unaffected by the laser fields. Ponderomotive forces arise due to the effect of laser field on the electron trajectory. If one or more laser beams propagating along z axis, interact with a relativistic electron traveling along z-axis. Typically a vacuum acceleration schemes are connected with the term $v_z E_z$, where $v_z \simeq c$, such that the energy gain is determined by the integral $\int dz\, E_z$. If the transverse electric field $E_\perp$ of the laser is finite along the z-axis, a transverse velocity $v_\perp$ will be introduced. For nonzero energy gain by using laser field in vacuum, one or more of the assumptions in the LW theorem must be violated. For example, a finite interaction region can be considered. However, this may be difficult to achieve in actual due to high-intensity requirement on the laser field and the damage threshold limitations of optical components. Alternatively, one can rely on nonlinear forces to produce the desired acceleration, such as the ponderomotive force. This leads to substantial energy gains even in the limit of infinite interaction region.

One approach for electron acceleration is to make use of laser beam in the far field limit i.e. in the region that is far from boundaries. There are difficulties for electron acceleration by laser in the far field. Many acceleration schemes in vacuum have been proposed based on ponderomotive forces, inverse processes, and a tightly focused laser and so on.

Hora was the first to treat the vacuum acceleration by non linear mechanics. The major difficulty in using a laser beam in vacuum to accelerate the electrons is that phase velocity of electric field of accelerated electrons is larger than the speed of light. However, theoretical analysis shows that the electrons may be accelerated when the phase slip is within the range of

accelerating phase. The electron energy gain during acceleration in vacuum mainly depends on the laser intensity because the longitudinal momentum of the electron is proportional to square of the amplitude.

REVIEW OF LITERATURE

Steinhauer(1992) proposed a new approach for laser particle acceleration in vacuum. The critical issue in any vacuum acceleration scheme is the inherent backward slippage of the particle relative to the laser beam phase, causing the particles to experience successive accelerations and decelerations. The difficulties can be overcome in a VLA scheme based on three elements: (i) an axisymmetric, radially polarized laser beam; (ii) an axicon focus aligned with the particle beam path; and (iii) the approximate matching of particle and laser phase. Consequently an acceleration gradients approaching 1 GeV/m over an interaction length of a few centimetre are predicted for 1013 W laser peak power at 10.6 pm.

Esarey *et al.* (1995) have reviewed, analyzed and discussed several features of vacuum laser acceleration including electron acceleration by two crossed laser beams and acceleration by a higher-order Gaussian beam. In addition, the vacuum beat wave accelerator (VBWA) concept is proposed and analyzed. It is shown that acceleration by two crossed beams is correctly described by the Lawson-Woodward (LW) theorem, i.e. no net energy gain for a relativistic electron interacting with the laser fields over an infinite interaction distance. Finite net energy gains can be obtained by placing optical components near the laser focus to limit the interaction region. The specific case of a higher-order Gaussian beam reflected by a mirror placed near focus is analyzed in detail. It is shown that the damage threshold of the mirror is severely limiting, i.e. substantial energy gains require very high electron injection energies. The VBWA, which uses two co propagating laser beams of different frequencies, relies on nonlinear ponderomotive forces, thus violating the assumptions of the LW theorem. Single-particle simulations confirm that substantial energy gains are possible and that optical components are not needed near the focal region.

Haaland (1995) involves pairs of intersecting linearly-polarized Gaussian-profile laser beams that are focused at crossover in vacuum and phased such that transverse field components cancel. The E_z component accelerates properly-phased *z*-axis relativistic electrons throughout a

half-wave slip distance centered at crossover. The slip length is approximately 90λ for the case considered, where λ is the wavelength of laser beam. The E_z component vanishs rapidly before and after this slip region, thus providing conditions for a special case that is not included in Palmer's general acceleration theorem. Electron energy-gain gradients of several GeV/m appear to be possible.

Free electrons have been accelerated in vacuum to MeV energies by a high-intensity subpicosecond laser pulse (10^{19} W/cm^2, 300 fs). Around the laser focus, the laser electric field makes electrons oscillate along the polarization direction, and simultaneously accelerate them along the propagation direction. Malika *et al*. (1997) observed that the experimental data are in good agreement with the relativistic motion of electrons in a spatially and temporally finite electromagnetic field, both in terms of maximum energy and scattering angle.

By utilizing the high-power, radially polarized CO_2 laser and high-quality electron beam at the Brookhaven Accelerator Test Facility, a vacuum laser acceleration scheme is proposed by Liu *et al*. (1999). In this scheme, optics configurations are simple, a small focused beam spot size can be easily maintained, and optical damage becomes less important. At least 0.5 GeV/m acceleration gradients are achievable by 1TW laser power.

Cyclotron-resonance energy gain of injected electrons subjected to an intense circularly polarized laser field and the magnetic field induced in low-density plasma is investigated theoretically by Zeng (1999). By considering the inverse Faraday Effect, where a circularly polarized finite area laser beam induces an axial magnetic field in plasma, it is found that very interesting energy gains can be obtained by Doppler-shifted cyclotron resonance in this field for the appropriate injection velocity. This same IFE field also acts to confine these electrons radially and, on exiting the plasma adiabatically, it is in this way that the transverse electron energy is converted to axial energy. Two limits to the energy gain are discussed: (1) cyclotron radius of the energetic electrons becoming comparable to the beam, and (2) axial dephasing.

Acceleration of electrons in low-density plasma in front of a solid target by a propagating short ultra-intense laser pulse is studied by Yu *et al*. (2000). When the laser is reflected at the target surface the accelerated electrons, with energy scaling as the laser intensity, continue to move forward inertially and thus escape from the pulse. Electrons accelerated

backwards by the reflected light can attain even higher energies due to their longer acceleration length and their high initial momentum from a relativistic return current.

Sprangle *et al*. (2000) have studied that to achieve multi-GeV electron energies in the laser wake-field accelerator (LWFA) it is necessary to propagate an intense laser pulse long distances in plasma without disruption. A 3D envelope equation for a laser pulse in a tapered plasma channel is derived, which includes wake-fields and relativistic and non-paraxial effects, such as finite pulse length and group velocity dispersion. They have shown that electron energies of ~GeV in a plasma-channel LWFA can be achieved by using short pulses where the forward Raman and modulation nonlinearities tend to cancel. Further energy gain can be achieved by tapering the plasma density to reduce electron de-phasing.

Ultra intense laser interactions with highly charged ions are investigated using three-dimensional Monte Carlo simulations. Results show that ultra energetic GeV electrons may be produced for highly charged ions chosen so that their electrons remain bound during the rise time of the laser pulse, and so that the electrons are ionized when the laser is near its maximum amplitude, which satisfies the best injection condition for subsequent laser acceleration (Hu and Starace 2002).

Electron acceleration by a laser pulse having Gaussian radial and temporal profiles of intensity has been studied by Singh (2004) in the presence of static magnetic field in vacuum. The starting point of the magnetic field has been taken around the point where the peak of the pulse interacts with the electron and the direction of the static magnetic field is taken to be the same as that of the magnetic field of the laser pulse. The electron gains considerable energy and retains it in the form of cyclotron oscillations even after the passing of the laser pulse in the presence of an optimum static magnetic field. The optimum value of the magnetic field decreases with laser intensity and initial electron energy. The energy gain also depends upon the laser spot size and peaks for a suitable value. The energy gained by the electron increases with laser intensity and initial electron energy. The electron trajectory and energy gain for different parameters such as laser intensity, initial electron energy, and laser spot size have been presented.

Niu *et al*. (2005) proposed a new method for implementing an axially-symmetric and radially-polarized beam through appropriate phase modulation of two orthogonally polarized

waves by using the designed DPEs (diffractive phase elements) placed outside the laser resonator. The incident 45° polarized uniform plane wave is demultiplexed into the o- and e-light waves after passing through the first designed DPE, made of birefringent material, and generates two linearly polarized L-TEM_{01} modes with orthogonal polarizations on the output plane. Superposition of the two L-TEM_{01} modes after appropriate phase compensation by using the second designed DPE can create the desired radially-polarized beam and numerical computational results demonstrate that the designed system can achieve the pre-assigned goal well.

The lowest-order axicon fields of a petawatt-power laser beam, focused down to a micron-size focal spot, can accelerate electrons from rest to GeV energies. Acceleration results primarily from interaction with the axial electric field component, while the remaining nonzero field components help mainly to confine the electron to a straight-line trajectory along the laser propagation direction. This picture already hints at the possibility of getting a well collimated accelerated electron beam in a laboratory setup. More practically useful conclusions about electron acceleration may be arrived at from simulations involving an electron bunch, rather than just a single electron. Salamin (2006) considered only electrons born at rest, may be from ionization. A peta-watt laser system consumes much more power than the entire electrical generating capacity of the United States and a continuous peta-watt beam is not a reality yet. An atom subjected to peta-watt power fields gets ionized (and its electrons scatter in all directions) quickly and long before the peak intensity is reached. Finally they make the remark that the lowest-order fields may not model the tightly focused beam accurately. Proper description of the fields in the regime of tight focusing requires inclusion of terms of higher order in the diffraction angle ε.

Singh (2006a) has studied that by using a relativistic three-dimensional single-particle code, acceleration of electrons created during the ionization of nitrogen and oxygen gas atoms by a laser pulse. Barrier suppression ionization model has been used to calculate ionization time of the bound electrons. The energy gained by the electrons peaks for an optimum value of laser spot size. The electrons created near the tail do not gain sufficient energy for a long duration laser pulse. The electrons created at the tail of pulse escape before fully interacting with the trailing part of the pulse for a short duration laser pulse, which causes electrons to retain

sufficient energy. If a suitable frequency chirp is introduced then energy of the electrons created at the tail of the pulse further increases.

Singh (2006b) has studied the dynamics of electron by linearly polarized laser in the presence of intense ultra short-duration magnetic field in vacuum. Resonance occurs between the electrons and electric field of the laser pulse for an optimum value of magnetic field, and the electron absorb significant energy. The value of the optimum magnetic field is nearly independent of the laser intensity and decreases with the initial electron energy .The acceleration gradient increases with laser intensity and decreases with initial electron energy.

Singh (2006c) has also investigated the dynamics of electron by circularly polarized laser pulse in the presence of an intense ultra short duration axial magnetic field in vacuum. This scheme has advantage of high energy and low emittance over other schemes of laser driven electron acceleration in vacuum.

Laser-induced acceleration of an electron injected initially at an angle to the direction of a short laser pulse with frequency variation in the presence of an axial static magnetic field has been investigated by Gupta and Suk (2006). Due to the combined effect of frequency variation of the laser and a magnetic field, the electron escapes from the laser pulse near the pulse peak. The electron gains considerable energy and retains it even after passing of the laser pulse in the presence of magnetic field in vacuum. The frequency variation plays an important role to enhance the electron energy in the presence of a static magnetic field in vacuum.

Gupta *et al*. (2007) have analyzed the acceleration of free electron in vacuum by a radially polarized laser. They utilized the unique properties of a radially polarized laser for electron acceleration in vacuum. The ponderomotive force due to the laser pushes the electron in forward direction. The significant enhancement in electron energy is due to the fact that radial field vanishes on axis, but only longitudinal field survives which accelerates the electron axially. The electron gains high energy, even though it is initially at rest. An electron at rest that is accelerated to relativistic energy tends to get out of phase with the field. Therefore, little MeV net energy was retained by a rest electron. However, for very high laser intensity, the rest electron can retain higher energy, because the electron leaves the interaction region before being decelerated, second, if an optimum magnetic field is applied during the trailing part of the laser pulse, the electron can gain and can retain significant energy in the form of cyclotron oscillations.

Singh and Malik (2008) studied the acceleration of electrons generated during ionization of the helium and nitrogen gases by a laser pulse in the presence of an intense magnetic field. The electrons generated from the low atomic number gases gain energy in GeV due to the resonance between the electrons and the electric field of the laser in the presence of magnetic field. It is shown that collimated GeV electrons with small energy spread can be obtained from the ionization of helium and nitrogen and quality of the electron beam is significantly enhanced. Also, the resulting electron beam is collimated and quasi-monoenergetic.

Laser driven acceleration of electrons lying along the axis of the laser has been studied by Singh *et al*. (2008). They have considered a linearly polarized laser pulse, the quiver amplitude causes electrons to escape from the pulse. The energy gained by the electrons for suitable value of the laser spot size. The value of a suitable laser spot size increases with laser intensity and initial electron energy. The energy gained by the electrons depends upon its initial position with respect to laser pulse. The electrons close to the pulse peak with initial phase $\pi/2$ are scattered least and gain higher energy. The electron close to the leading edge of the pulse gain sufficient energy for a short laser pulse and effect of initial phase is not important. A suitable value of laser spot size can be estimated from this study.

The resonance acceleration of plasma electrons in interaction of an intense short pulse laser with underdense plasma is theoretically and numerically studied by Niu *et al*. (2008). They used a test particle model, where the joint effect of the circularly polarized (CP) Gaussian laser fields and the self-generated quasi-static fields, including the radial quasi-static electric (QSE) field, the azimuthal quasi-static magnetic (QSM) field, and the axial QSM field, is included. They found that the resonance takes place when the betatron oscillation frequency of electrons in self-generated quasi-static fields coincides with the Doppler shifted laser frequency. Due to resonant acceleration, some electrons attain energy directly from the laser pulse and thus form a well qualified relativistic electron beam (REB) with high energy, quasi-monoenergy and extreme low divergent angle. It is also found that the final energy of the REB increases with laser intensity but decreases with plasma density. Our results show that the REB produced by CP laser plasma interaction has better collimation comparing to the linearly polarized (LP) case for the resonant electrons move helically within a Larmor radius induced by the axial QSM field

Kaplan *et al.* (2009) demonstrated the feasibility of multi-MeV electron acceleration corresponding to ~ 0.1 TeV/cm acceleration gradients, based upon strong inelastic scattering of

electrons in an ultra-gradient relativistically-intense laser field. Inelastic scattering even in low-gradient laser field may induce extremely tight temporal focusing. They also predicted the formation of zepto-second electron bunches due to strong after-scattering electron beam modulation.

Manaut *et al.* (2009) present a study of Mott scattering of polarized electrons in the presence of a laser field with circular polarization using the helicity formalism and the introduction of the well-known concept of nonflip differential cross section as well as that of flip differential cross section. The results they had obtained in the presence of a laser field are coherent with those obtained in the absence of a laser field. They compared their results with the process of Mott scattering of polarized electrons in the presence of a laser field with linear polarization. Some differences in the theoretical results were also obtained.

Singh and Manoj (2011) studied the acceleration of electrons by a radially polarized intense laser pulse. The laser spot size, laser pulse duration, initial phase, and relative position of the electrons with respect to laser pulse affect electron acceleration. A right choice of laser spot size and injection is needed to achieve GeV electrons. The electrons follow a nearly straight line path which shows that acceleration is due to the longitudinal electric field of the laser. Electron energy decreases for the electrons originating away from the axis of the laser pulse. The electrons generated close to the peak of laser pulse gain higher energy than other electrons. The initial phase dependence is also shown by the electrons lying along the axis of the laser pulse. A right choice of laser parameters is needed to obtain high energy quasimonoenergetic collimated electron beams.

SIGNIFICANCE

Electron acceleration in vacuum-

- With the help of laser, electron can be accelerated in vacuum up to the range of GeV energies.

- For a suitable position of the peak of the pulse, the ponderomotive force due to the laser pushes the electron forward in the leading part of the pulse and electron get accelerated rapidly.
- The electron gains high energy (about 750 MeV), even it is at rest.
- The electrons retain the energy even after passing of the laser pulse in the presence of a magnetic field. Hence, the magnetic field and the polarization of the laser pulse enhance the energy of accelerated electron in vacuum.
- Laser based accelerators are capable of producing high energy electrons/protons in much shorter distances than conventional accelerators due to the large electric fields associated with laser.
- The higher group velocity of a laser and the absence of plasma instabilities have some advantage over a plasma to choose vacuum as a medium for electron acceleration and this also makes it easier to inject preaccelerated electrons in vacuum.
- Injection of pre-accelerated electrons in vacuum increases the duration of the interaction between the laser pulse and the electron, thus increasing the energy gain.

Electron acceleration in plasma:

- Plasmas are capable of sustaining extremely high amplitude electric fields that can be used to accelerate particles to high energies, in distances orders of magnitude shorter than in conventional accelerators.
- The acceleration of electrons using laser-plasma interaction has attracted much attention due to the greater acceleration gradient (above 100 GV/m) than radio frequency accelerators.

OBJECTIVES

1. To investigate the laser induced electron acceleration in vacuum with azimuthal magnetic field.

   Abstract- The electron rotates around the propagation direction of the laser pulse during the interaction with **circularly polarized** intense laser pulse. Resonance occurs between the electrons and electric field of the laser pulse for optimum values of the magnetic fields, and the electrons gain much higher energies. The resonance is stronger at higher values of the magnetic field. The values of magnetic fields at which resonance occurs depend upon the laser intensity and plasma density, and initial electron energy. The electrons with less initial energy find more time to interact with the laser pulse and gain more energy than the electrons with more initial energy. Electron trajectory and energy gain for different parameters can be obtained.

2. To investigate the electron acceleration of a radially polarized laser in a tapered magnetic wiggler.

   Abstract- The acceleration of electrons by a laser pulse, in the presence of a magnetic wiggler, in vacuum and plasma can generate an electron with high energy gain. The vector potentials of the laser pulse and magnetic wiggler can be defined in terms of the tapering parameter. For a specific value of tapering parameter dependence, *the* energy gained by the electron increases. The resonance condition is sensitive to the electron energy and the electron density of the medium. It can be maintained for longer duration for a suitably tapered wiggler period and the electron can gain much higher energy.

3. To investigate the effect of chirping on electron acceleration by a radially polarized laser in vacuum.

   Abstract- The electrons accelerated by a laser pulse without a frequency chirp are known for poor-quality beams. If a suitable frequency chirp is introduced, then the energy of the electrons increases significantly. GeV electrons can be produced using a right choice of laser spot size, frequency chirp, and pulse duration.

4. To investigate the chirping with circularly polarized laser in vacuum and plasma.

   Abstract- The electrons accelerated by a laser pulse without a frequency chirp are known for poor-quality beams. If a suitable frequency chirp is introduced, then the

energy of the electrons increases significantly. The maximum energy of the electrons gets enhanced for a circularly polarized in comparison to a linearly polarized laser pulse due to axial symmetry of the circularly polarized pulse. The variation of electron energy with laser spot size, laser intensity, initial electron energy, and initial phase can be studied.

5. To study the electron acceleration in cluster plasma.

Abstract- The acceleration of electrons using laser-plasma interaction has attracted much attention due to the greater acceleration gradient (above 100 GV/m) than radio frequency accelerators. Cluster is also a good medium for laser plasma accelerator. High absorption efficiency of the laser energy and plasma channel formation are vitally important to electron acceleration. For practical application such as nondestructive material inspection, high-quality electron beams are required. The generation of electrons with good spatial quality and monoenergetic distribution can be explored.

Electron Dynamics

Consider a radially polarized laser beam with electric field

$$\vec{E} = \hat{e}_r E_r + \hat{e}_z E_z$$

$$E_r = E_0 \frac{r}{r_0 f^2} sin(\phi) exp[-\frac{r^2}{r_0^2 f^2}], \quad (1)$$

$$E_z = -E_0 \frac{2}{k_0 r_0 f^2} [\left(1 - \frac{r^2}{r_0^2 f^2}\right) \cos(\phi) - \frac{z r^2}{R_d r_0^2 f^2} \sin(\phi)] exp\,[-\frac{r^2}{r_0^2 f^2}], \quad (2)$$

where $\phi = k_0 z - \omega_0 t - 2tan^{-1}[z/R_d] + zr^2/(R_d r_0^2 f^2) + \phi_0$,

$f^2 = 1 + [z/R_d]^2$, $k_0 = \omega_0/c$, $R_d = k_0 r_0^2 / 2$ is the Rayleigh length,

r_0 is the minimum laser spot size, ω_0 is laser frequency, c is speed of light in vacuum and f is beam width parameter of the laser.

The magnetic field related to laser pulse can easily be deducted from Maxwell's equations.

So the magnetic field related to laser pulse is given by:

$$\overrightarrow{B_L} = \frac{\vec{k}\times\vec{E}}{\omega}, \qquad (3)$$

The externally applied short duration intense axial magnetic field given by

$$B_z = B_0 \exp\left[-\frac{t^2}{\tau_b^2}\right] \hat{e}_z, \qquad (4)$$

where τ_b^2 is the duration of the magnetic field. The electric field related to the axial magnetic field is very small as compared to electric field of the laser and its inclusion does not make any difference.

The final equations governing electron momentum and energy are following:

$$\frac{dp_r}{dt} = -e[E_r[1-\frac{v_z}{c}] + v_r B_0 \exp\left[-\frac{t^2}{\tau_b^2}\right]], \qquad 5(a)$$

$$\frac{dp_z}{dt} = -e[E_z + \frac{v_r E_r}{c}], \qquad 5(b)$$

$$\frac{d\gamma}{dt} = \frac{-e}{m_0 c^2}[\vec{v}\cdot\vec{E} + v_r^2 B_z]. \qquad 5(c)$$

To normalize these equations time and length are normalized by $1/\omega_0$ and c/ω_0 respectively. Velocity, momentum and energy are normalized by c, m_0c and m_0c^2 respectively. The normalized laser intensity and magnetic field-strength parameters are expressed as $a_0 = (eE_0/m_0\omega_0 c)$ and $b_0 = (eB_0/m_0\omega_0)$

$$\frac{dv_r'}{dt'} = -\frac{a}{\gamma}\frac{r'}{f^2}\sin(\phi)\exp\left[-\frac{r'}{f^2}\right][1 - v_z'] - \frac{b}{\gamma}v_r' exp\left[-\frac{t'^2}{\tau_b'^2}\right]. \quad (6)$$

$$\frac{dv_z'}{dt'} = [[\frac{2a}{\gamma k_0 r_0 f^2}\left[1 - \frac{r'^2}{f^2}\right]\cos(\phi) - \frac{2a}{\gamma k_0 r_0 f^2}z' r'^2 \sin(\phi)]$$

$$exp\,[-\frac{r'^2}{f^2}] - \frac{a}{\gamma}v_r'\frac{r'}{f^2}sin(\phi)exp\,[-\frac{r'^2}{f^2}]]. \quad (7)$$

$$\frac{d\gamma}{dt'} = -a\,v_r'\frac{r'}{f^2}\sin(\phi)\exp\left[-\frac{r'}{f^2}\right] + av_z'\frac{2}{k_0 r_0 f^2}[\left(1 - \frac{r'^2}{f^2}\right)\cos(\phi)$$

$$-\frac{z' r'^2}{f^2}\sin(\phi)]exp\,[-\frac{r'^2}{f^2}] - bv_r'^2 exp\left[-\frac{t'^2}{\tau_b'^2}\right]. \quad (8)$$

Now we will use these normalized equations of electron momentum and Energy. Simulations will be carried out by solving the momentum and energy equations using a relativistic single particle computer program developed in Mathematica.

METHODOLOGY

1. Formulation of hypothesis

The hypothesis is based on the application of magnetic field to vacuum and plasma to see its effect on electron-acceleration by a laser. In the presence of magnetic field of suitable value, electron can gain significant energy. Equation of momentum and energy will be derived and will be solved numerically by using MATHEMATICA software. The results will be plotted in ORIGIN software.

2. Sources of data

Theoretical results will be compared with experimental results collected through various research papers.

3. Research Design:

Numerical and analytical analysis

Tools:

MATHEMATICA and ORIGIN software.

REFERENCES

- Esarey, E.; Sprangle, P.; Krall, J. (1995), "Laser acceleration of electrons in vacuum", *Physical Review E,* **52**(5), 5443-5453

- Gupta, D.N.; Suk, H. (2006), "Combined role of frequency variation and magnetic field on laser electron acceleration", *Physics of Plasmas*, **13**, 013105(1-6)

- Gupta, D.N.; Kant, N.; Kim, D.E.; Suk, H. (2007), "Electron acceleration to GeV energy by a radially polarized laser", *Physics Letters A,* **368**, 402-407

- Haaland, C.M. (1995), "Laser electron acceleration in vacuum", *Optics Communications,* **114**, 280-284

- Hu, S.X.; Starace, A.F. (2002), "GeV electron from ultraintense laser interaction with highly charged ions", *Physical Review Letters,* **88**(24), 245003(1-4)

- Kaplan, A.E.; Pokrovsky, A.L. (2009), "Laser gate: multi-MeV electron acceleration and zepto-second e-bunching", *Optics Express,* **17**, 6194-6202

- Liu, Y.; Cline, D.; He, p. (1999), "Vacuum laser acceleration using a radially polarized CO_2 laser beam", *Nuclear Instruments and methods in Physics Research A,* **424**, 296-303

- Malika, G.; Lefebvre, E.; Miquel, J.L. (1997), "Experimental observation of electrons accelerated in vacuum to relativistic energies by a high intensity laser", *Physical Review Letters,* **78**, 3314-3317

- Manaut, B.; Attaourti, Y.; Taj, S.; Elhandi, S. (2009), "Mott scattering of polarized electrons in a circularly polarized laser field", *Physica Scripta*, **80**, 025304(1-10)

- Niu, C.H.; Gu, B.Y.; Dong, B.Z.; Zhang, Y. (2005), "A new method for generating axially-symmetric and radially-polarized beams", *Journal of Applied physics D: Applied Physics*, **38**, 827-832

- Niu, H.Y.; He, X.T.; Qiao, B.; Zhou, C.T. (2008), "Resonant acceleration of electrons by intense circularly polarized Gaussian laser pulses", *Laser and Particle Beams,* **26**, 51-59

- Salamin, Y.I. (2006), "Electron acceleration from rest in vacuum by an intense Gaussian laser beam", *Physical Review A,* **73**, 043402(1-6)

- Singh, K.P. (2004), "Electron acceleration by an intense short pulse laser in a static magnetic field in vacuum", *Physical Review E,* **69**, 056410(1-5)

- Singh, K.P. (2006a), "Self-injection and acceleration of electron during ionization of gas atoms by a short laser pulse", *Physics of Plasmas,* **13**, 043101(1-6)

- Singh, K.P. (2006b), "Electron acceleration by a linearly polarized laser pulse in the presence of a pulsed intense axial magnetic field in vacuum", *Journal of Optical Society of America B,* **23**, 1650-1654

- Singh, K.P. (2006c), "Acceleration of electrons by a circularly polarized laser pulse in the presence of an intense axial magnetic field in vacuum", *Journal of Applied Physics,* **100**, 044907(1-4)

- Singh, K.P.; Malik, H.K. (2008), "Collimated GeV electrons from the ionization of a gas by a laser pulse in an intense magnetic field", *Applied Physics Letters,* **93**, 044101(1-3)

- Singh, K.P.; Gupta, D.N.; Malik, H.K. (2008), "The effect of laser pulse parameters and initial phase on the acceleration of electrons in a vacuum", *Physica Scripta,* **77**, 045401(1-6)

- Singh, K.P.; Manoj, K. (2011), "Electron acceleration by a radially polarized laser pulse during ionization of low density gases", Phys. Rev. ST Accel. Beams 14, 030401 (2011)

- Sprangle, P.; Hafizi, B.; Penano, J.R.; Hubbard, R.F.; Ting, A.; Zigler, A.; Antonsen, T.M. (2000), "Stable laser-pulse propagation in plasma channels for GeV electron acceleration", *Physics Review Letters,* **85**, 5110-5113

- Steinhauer, L.C.; Kimura, W.D. (1992), "A new approach for particle acceleration in vacuum", *J. Appl. Phys.,* 72(8), 3237-3245

- Tsakiris, G.D.; Gahn, C.; Tripathi V.K. (2000), "Laser induced electron acceleration in the presence of static electric and magnetic fields in a plasmas", *Physics of Plasmas,* **7**, 3017-3030

- Umstadter, D.; (2001), "Review of physics and applications of relativistic plasmas driven by ultra-intense lasers", *Physics of Plasmas,* **8**, 1774-1785

- Yu, W.; Bychenkov, V.; Sentoku, Y.; Yu, M.Y.; Sheng, Z.M.; Mima, K. (2000), "Electron acceleration by a short relativistic laser pulse at the front of solid targets", *Physical Review Letters,* **85,** 570-573

- Zeng, G. (1999), "Energy gain of injected electrons subjected to an intense laser field and its magnetic field induced in plasma", *Physical Review E,* **60**, 5950-5958